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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Research Report 17

COLD EXPANSION AND INTERFERENCE FOR EXTENDING THE FATIGUE LIFE OF MULTI-LAYER METAL JOINTS

by

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COLD EXPANSION AND INTERFERENCE FOR EXTENDING THE FATIGUE LIFE OF MULTI-LAYER METAL JOINTS

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SUMMARY

The influences of both hole cold expansion and interference-fit fasteners for extending the fatigue life of multi-layer aluminium alloy joint specimens under variable-amplitude loading have been examined experimentally. Improvements in fatigue life were markedly dependent on the degree of load transfer in the specimen joint. The cold expansion of fastener holes enhanced fatigue life in low-load-transfer joints but not in 100%-load-transfer joints. The use of interference-fit fasteners, especially at high degrees of interference, was an effective means of life improvement irrespective of proportion of load transfer. Interfacial fretting limited the improvement in fatigue life of low-load-transfer joints to a factor of about 6, and, although some fretting occurred in 100%-load-transfer joints it was not determinative, and a 40-fold increase in fatigue life was obtained with a combination of hole cold expansion and interference-fit fastener.

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1. INTRODUCTION

Most, if not all, of the processes currently used to increase fatigue life were developed during the period when design lifing philosophies for metal aircraft structures did not take into account the benefits available. Rather, the philosophy adopted was to use the potential increases as a safeguard; the processes were used only to extend life beyond that otherwise deemed safe, or to reclaim it when premature cracks were found. This philosophy has now changed. Some recent high-performance military aircraft, at least, use established life enhancement techniques in the manufacturing process. An example is the McDonnell Douglas F-18 which uses shot peening, hole cold expansion, ring pad coining, and interference-fit fasteners in order to achieve the design life. The quests for higher performance and economic value now make it more important than ever not only to quantify the life improvements but to ensure that they are optimum.

Possibly the technique most widely used in engineering practice to improve the fatigue life of metal components with holes is the Boeing split-sleeve cold-expansion process now marketed by Fatigue Technology Inc., Seattle, USA. Fatigue life increases by factors up to about 10 or more have been reported for this process [1-3], though factors of 2 to 5 are more common [4-6]. The actual magnitude depends on a number of process and testing variables, and generally increases with life. It is commonly thought that the life improvements arise from the resultant compressive residual stress field surrounding the plastically expanded hole, leading to a reduction in the mean fatigue stress level in the local regions where cracks eventually initiate. The application of hole cold expansion to multi-layer joints has received only limited attention, yet most holes exist for the purpose of joining two or more layers of material. An investigation by Mann et al. [7] into the life improvements by cold expansion of three-layer aluminium alloy stacks, has given the following results:

- for single-layer open-hole specimens (though cold expanded with side plates) the life improvement ratio was 7.7,

- for low-load-transfer two-fastener joint specimens the life improvement ratio was 2.6,

- for the latter specimens, cracking was initiated by fretting between the faying surfaces about 3 mm from the edge of the hole where the cold expansion caused surface protrusions in both specimens and side plates.

It appears that fretting initiation of fatigue cracks may prevent the full benefit of cold expansion being realised in multi-layer metal joints. Fretting arises from the relative movements of opposing surface asperities; such movements, often, may be of the order of only 100 *nm*. These motions can quickly rupture any oxide film, leading to cold welding of the asperities and then their fracture from high strain fatigue. Material is thus transferred from one surface to the other, gouges and pits are formed, and stress concentration rapidly occurs leading to early crack initiation and growth [8]. This process is particularly potent at the junction of slip/no slip regions on the surface.

If relative movements could be limited in joint faying surfaces the benefits of cold expansion of the fastener holes might be expected to be greater than otherwise. In aircraft construction clamping forces via fastener torques are usually standardised and hence are not a ready means available to reduce relative movements. It was thought, however, that a reduction could be achieved by the use of interference-fit fasteners, a common method in its own right for improving fatigue life. The interference fit would give a preloading effect which, though increasing the mean fatigue stress at the point of maximum stress concentration at the edge of the hole, decreases the alternating component of the stress and hence the degree of relative movement.

This report describes an experimental examination of the influence of fastener interference on the fatigue life of non-secondary-bending multi-layer aluminium alloy specimens with cold-expanded holes. Given the possible role of fretting and its dependence on the amount of relative movement, which in turn depends on the load transfer characteristics of the joint, both low-load-transfer and 100%-load-transfer joints have been examined.

2. SPECIMENS

All specimens (excluding side plates and fasteners) were manufactured from 45 mm thick rolled plates of 2214-T651 aluminium alloy, the loading direction being the longitudinal direction of the plate. The side plates were machined from 2024-T4 rectangular-section extruded bar, and the fasteners were of high-tensile steel and were ground to produce specific diametral interferences. The configurations of the low-load-transfer and the 100%-load-transfer bolted joint specimens are shown in Fig. 1.

Prior to assembly the contacting faces of the cover plates and the specimens were polished with a final finish of 800 grade paper in the longitudinal direction of the specimens. Unless noted otherwise, the polished faces were clamped together, after degreasing, without any interface lubrication or treatment. All cold expansions of the three-layer stacks used the Fatigue Technology Inc. split-sleeve process and tooling, and were made in a jig which aligned the holes in the three layers and kept the stack clamped during the expansion, subsequent reaming, fastener insertion and nut tightening. The full process was applied to one hole at a time. The fastener insertion procedure consisted of degreasing the fastener and hole, lubricating both with barium chromate grease, and forcing the fastener (for those with an interference fit) through the hole using the tapered lead and the cylindrical integral washer as guides for centrality. Interference fastener insertion was made in a servohydraulic test machine and force-displacement plots were obtained mainly for quality control. All fasteners were clamped to a standard torque of 19.2 Nm.

Specimens were assembled with hole cold expansions of either zero or 4%, and fastener interferences of either zero, 0.5%, 1.5%, or 3% (three 100%-load-transfer specimens only). Table 1 lists the cold expansion details and the hole and fastener diameters which produced these conditions.

3. LOW-LOAD-TRANSFER JOINTS

3.1 Testing and Results

Specimens were tested in a standard servohydraulic fatigue test machine of 600 kN capacity with computer control to specify and monitor the load sequence applied. The load sequence employed was of a flight-by-flight type developed from the stress history of a fuselage bulkhead of a fighter aircraft - specifically the FS488 bulkhead of Australian F/A-18 aircraft 103 [9]. The sequence has a program length of 18,648 turning points which is equivalent to 255.4 flight hours and the average cyclic frequency used was 1.86 Hz. All tests were made at a maximum net-area stress of 350 MPa, as referred to the central portion of the three-layer stack, this stress being chosen to give lives typical of fighter aircraft.

The combinations of cold expansion and interference fit were as noted above, that is, expansions were either zero or 4%, and fastener interferences were either zero, 0.5%, or 1.5%. Four specimens were tested under each combination and the results, in flying hours, are given in Table 2(a). Figure 2 is a logarithmic plot of lives enabling visual comparisons of performance.

Non-cold-expanded specimens with neat-fit fasteners failed, as expected, at the minimum section across one of the fastener holes. All other specimens had some form of hole life enhancement treatment and tended to make the traditional failure region, that is, across the holes, superior in fatigue life to other parts of the specimen. These tended to fail from the stress concentration of the fillets which joined the test section to the grip portion of the specimen. Fillet failure was overcome by rounding the square fillet edges and shot-peening the fillet regions, again forcing failure to within the test section. The results shown in Table 2 are from specimens, all of which, for consistency, had the fillet regions shot-peened.

3.2 Statistical Analysis

An examination of Table 2(a) or Fig. 2 indicates a substantial increase in fatigue life by cold expansion and by the use of interference-fit fasteners. It is not clear, however, that combinations of these processes have any added advantage. The fatigue lives were analysed using a two-way analysis of variance and the standard t-test for significance between means; the analyses used the logarithm of the life and a significance level of 0.05. The results are best described in relation to Table 3 which lists several ratios of mean lives.

Cold expansion of the fastener holes, by itself, significantly increases life—by a factor of about four. It is also clear from Table 3 that there is no significant effect of cold expansion in the presence of interference-fit fasteners. Likewise, fastener interference, by itself, also significantly increases life, this time by a factor of about six. There is also significant interaction, that is, the effect of fastener interference is dependent on the degree of cold expansion; the factor of six just mentioned is reduced to about 1.4 in the presence of cold expansion. This change is quite significant, but the factor of 1.4 itself is on the borderline of significance, that is, in the presence of cold expansion, fastener interference provides only a marginal further increase in life. Additionally, the change in interference from 0.5% to 1.5% has not influenced the fatigue life.

3.3 Fretting

The concept that fasteners with interference might eliminate the fretting associated with the surface protrusions adjacent to holes cold expanded as a multi-layer stack appears only partially satisfactory when considering the fatigue lives obtained experimentally—cold expansion gave a life improvement by a factor of 4, and interference-fit fasteners in such holes added a further factor of less than 1.5, which is on the borderline of significance. It might then be expected that fretting has been little alleviated by the use of interference.

Figures 3 and 4 show typical side plate fretting wear and the associated specimen fatigue fracture for holes with zero and 4% cold expansion respectively. For specimens with non-expanded holes, fatigue fracture with the neat-fit fasteners commenced at many sites along the bore of the hole probably resulting from fretting between the fastener shank and the surface of the hole—see Fig. 3(a). Fasteners with 0.5% interference allowed side-plate fretting to dominate the fracture mode—fatigue fracture initiating from fretting either near the hole edge, the specimen edge or the specimen face near the end of the side plates, a location of maximum relative movement, as shown in Figs. 3(b) and 5. Fasteners with 1.5% interference allowed similar modes though initiation near the hole was transferred to the regions just outboard of the hole in the loading direction, Fig 3(c). This was an area of severe fretting, where the out-of-plane displacements due to the interference were evident in combination with maximum relative displacements under the cyclic stress for this area.

For specimens with cold-expanded holes fretting also dominated. With neat-fit fasteners fatigue fracture initiated, mostly, adjacent to the hole along the centreline of loading, Fig. 4(a), and with interference-fit fasteners severe side plate fretting caused initiation to occur near the edges of the specimens, Fig. 4(b). These edge regions were the dominant sites for the main fracture although extensive cracking also occurred in the fretted regions around the holes, as illustrated in Fig. 6.

The previous work by Mann et al. [7] had indicated that for cold expansion the location of the maximum in the out-of-plane displacements did not always occur at the edge of the hole, depending to some degree on the stack-up details and the mandrel pulling direction. In the present tests it is likely that the maximum occurs in a circular band commencing about 1 mm from the edge of the hole, particularly for conditions of high interference. This is evident in Figs 4(b) and 6.

3.4 Discussion

It is apparent from the test lives and fracture modes described above that the aim to improve the life of cold-expanded multi-layer stacks by the use of interference-fit fasteners has not been achieved because of the intervention of crack initiation by interfacial fretting. As mentioned earlier, the benefits of cold expansion in a multi-layer stack appear to be limited by local fretting adjacent to the holes and it was thought that the use of interference-fit fasteners might overcome this problem. Such fasteners have given a small improvement in fatigue life but this arrangement also has run foul of fretting fatigue cracks initiating at other side-plate/specimen-surface regions.

Following the same logic, can the jointing details be arranged to eliminate fretting in the regions observed with the hope of a further increase in life? Two means seem possible [10]; the first is to decrease relative movements, and the second is to reduce interfacial friction. The second option was considered to be not viable in the present context: it would involve the use of surface lubricants, hence the load transfer capability of the joint would be degraded.

Decreasing the intensity of the relative movements appeared a promising strategy, since, if anything, load transfer would be increased. Using specimens which had 4% cold-expanded holes and 1.5% interference-fit fasteners two groups of procedures were examined. The first group attempted to relieve the very localized relative movements occurring around the fastener hole regions. One method was to carry out the cold expansion in the three-layer stack (using neat-fit fasteners), disassemble, repolish both side plates and specimen to remove out-of-plane material, and re-assemble with interference-fit fasteners. A second method was to ensure no relative movement between side plates and specimen around the hole by counterboring the side plates in this region. At the same time the edges of the side plates were radiused to allow a smoother pick-up of load by the side plates and hence give a more uniform load transfer and less fretting.

The other procedure for reducing the degree of relative movement was to use an interface layer to mechanically increase friction. A commercial product, 'Screenbak'*, an abrasive mesh, was used for this purpose. Two arrangements were examined. The first was to insert Screenbak between the side plates and the specimen before the cold expansion and fastener insertion. The second arrangement was to cold expand the three-layer stack without the Screenbak (using neat-fit fasteners), disassemble, re-polish to remove out-of-plane material on both specimen and side plates, insert Screenbak and re-assemble with the interference-fit fasteners.

Two multi-layer specimens for each of the four treatments above were assembled and tested under the same conditions as those noted previously, and the fatigue lives are given in Table 2(b). Again, the lives are presented graphically in Fig. 2, and it is evident that there have been no marked increases. Statistical tests confirmed that, compared with the condition of 4% cold expansion and 1.5% fastener interference, the fretting alleviation measures examined have been ineffective in increasing fatigue life. This may be seen from Fig. 7 where it is evident that although fretting in the vicinity of the fastener holes has been effectively reduced, fretting from other regions of the side plates has dominated resulting in no further life improvement.

Geometrically, the polishing and counterboring techniques make the specimens similar to those without cold expansion, that is there is no out-of-plane material capable of localised fretting, but even so, some life improvement was expected from the cold expansion residual stresses. In the event, fretting from other regions of the side plates intervened. Screenbak has been used for many years in the gripping sections of fatigue specimens, promoting load transfer and effectively minimising fretting-initiated failures from these regions. No such advantage was gained with the present specimens and it can be seen from Fig. 8 that the abrasions caused by the Screenbak initiate fatigue fracture.

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* Screenbak is an open nylon mesh impregnated with an abrasive, manufactured by Norton Pty Ltd. The particular product used in the present tests was Metalite Screenbak, with 360 grit aluminium oxide on a 3 mm square mesh.

It is apparent that good load transfer and no interfacial fretting are incompatible aims with low-load-transfer joints, leading to the situation where the potential for life improvements with hole cold expansion combined with interference-fit fasteners is not fully realised. For the more-practical case of higher load transfer joints it was thought that interfacial fretting would not dominate and that the full potential for improvements in life might be obtained. The next Section describes similar tests on 100%-load-transfer joints.

4. 100%-LOAD-TRANSFER JOINTS

4.1 Testing and Results

The specimens shown in Fig. 1(b) were designed to enforce failure through the 2214 aluminium alloy test material rather than allow fastener failure through either fatigue or static fracture. They were tested identically with the low-load-transfer specimens except the net-area stress was reduced to 230 MPa in order to give similar lives. Again, all combinations of cold expansion and interference fit, as mentioned above, were examined, and four specimens were tested under each combination except for the 3% interference fit, the results being given in Table 4. Figure 9 shows a logarithmic plot of the lives to indicate comparative performances.

All but two specimens failed through the fastener hole. The two exceptions were from the 4% cold expansion group with neat-fit fasteners, and had fastener failure lives of 990 and 1848 flight hours (which are similar to the two specimens which failed through the bolt hole—950 and 1242 flight hours). In retrospect, the condition that might encourage fastener failure should be when the hole is life enhanced by cold expansion and the fastener is able to suffer the most bending during load transfer, which is the neat-fit case where the support for the fastener is the smallest. The fact that the only failures to occur from fasteners were from this group is an indicator that although the specimen design was borderline for this case, it generally was quite satisfactory. Given that the fastener-failure specimens also had long fatigue cracks emanating from the hole (5.1mm long in one specimen and 3.7mm long in the other), and that the fastener-failure and hole-failure test lives were similar, the four lives are grouped together for analysis.

4.2 Statistical Analysis

The statistical tests described for analysing the results from the low-load-transfer specimens were applied also to the 100%-load-transfer specimens. The results are described in relation to Table 5 which lists various ratios of mean lives.

For neat-fit fasteners, that is, in the absence of interference fit, there is no significant influence of cold expansion on fatigue life. The factor of 1.23 shown in Table 5 is an apparent increase in life only, and is not statistically significant. In the presence of interference-fit fasteners, however, cold expansion significantly improves fatigue life, the life improvement factors range from about 4 to about 8, depending on the fit of the fastener. Said another way, in an overall sense, statistically there is a significant effect of cold expansion on fatigue life, but there is also significant interaction between cold expansion and degree of interference.

Except for the case of no cold expansion with 0.5% interference fasteners, there is a significant and progressive increase in fatigue life with increasing degree of interference. This statement applies to specimens with and without prior cold expansion of the holes. The maximum fatigue life is attained for the case of cold expansion combined with the maximum degree of fastener interference examined, namely, 3.0%.

In summary, compared with the baseline lives of specimens with no cold expansion and with neat-fit fasteners, cold expansion, by itself, gives no significant increase in life, interference fit, by itself, gives a maximum 5-fold improvement in life, but the combination of cold expansion and interference fit gives a maximum life improvement of more than 40-fold.

4.3 Fretting

Under all conditions of hole cold expansion and degree of interference of the fastener extensive fretting occurred between the fastener and the bore of the hole and this feature contributed to the many crack initiation sites along the bore. As mentioned above, all specimens, except the two which experienced fastener failure, failed through the fastener hole, and this has been assisted by the considerable fretting. Examples of this mode of failure are given in Figs 10 and 11. It is noticeable in Fig. 10 that there is a larger amount of fretting in the hole and on the initial regions of the fatigue fracture surface when the fastener has an interference fit, and this observation might seem at variance with the *longer* fatigue lives for this condition. The likely explanation is that with tighter fasteners the fretting products have less means of escape than with neat-fit fasteners, and with the looser neat-fit fasteners the damage in the bore of the hole may possibly be more of a spalling nature than true fretting.

There was fretting between the specimen faces and the sideplates for all conditions examined, examples of which are shown in Fig. 11, but it did not appear to contribute to the failure mode. For specimens with neat-fit fasteners the fretting was confined to regions around the hole, no doubt as a result of the deformation from the fastener tightening. Within this group the non cold-expanded specimens experienced face fretting at the locations of maximum relative movement around the hole, Fig. 11(a), whereas for the cold-expanded specimens the out-of-plane displacement areas around the hole were also regions of fretting, Fig. 11(b). The face fretting patterns of all specimens with interference-fit fasteners were similar—examples are given in Figs 11 (c) and (d). It is apparent that the face distortions in the three layer stack arising from both the interference of the fastener and its clamping are more complex than those when interference is not applied.

5. GENERAL DISCUSSION

5.1 Effect of Load Transfer on Life Enhancement

The present results clearly show that the effectiveness of two of the most common fatigue life enhancement techniques is markedly dependent on the degree of load transfer in a jointed specimen, and this dependence is illustrated in Fig. 12. For low-load-transfer

specimens, cold expansion of the fastener holes substantially increases fatigue life (a factor of about 4) whereas with 100%-load-transfer specimens it gives practically no improvement in life.

Again, the use of interference-fit fasteners as a means of extending life was quite effective with low-load-transfer specimens (a factor of about 6), but its effectiveness with 100%-load-transfer specimens depended on the degree of interference, being ineffective at 0.5% and progressing to a life improvement factor of about 5 at an interference of 3.0%.

The effectiveness of the combined treatment of cold expansion and interference fit was also influenced by the degree of load transfer. For low-load-transfer specimens the combined treatments gave a life improvement factor of about 6 (Table 3) which was independent of degree of interference. With 100%-load-transfer specimens the life improvement factor ranged from about 5 to about 40 (Table 5), increasing with amount of interference.

The maximum fatigue life with low-load-transfer specimens was obtained equally by several treatments, either with interference alone, irrespective of amount, or in combination with cold expansion. The maximum in life improvement was a factor of about 6 and was obviously limited by the side-plate fretting, either at out-of-plane regions near the holes resulting from the cold expansion or the interference fit of the fasteners, or at regions of maximum relative movement near the ends of the side plates. With 100%-load-transfer specimens the maximum fatigue life occurred with a combination of the maximum in both cold expansion and interference fit, and, as mentioned above, was a 40-fold increase over the life of specimens with no cold expansion and neat-fit fasteners. Side-plate fretting, though it occurred in these specimens, did not affect fatigue life.

5.2 Comparison of Present with Published Results

The present test conditions were intended to simulate some of the main variables that might be encountered in fatigue of aircraft structural joints, and although they differ from those pertaining to published work, still it is worth comparing present with published results where some relevance exists.

Schwarmann [2] has investigated both cold expansion and interference fit in high-load-transfer three-layer joint specimens of 7075 aluminium alloy tested under constant- and variable-amplitude loading. The life improvement factors obtained depended on the maximum stress, being greater at lower stresses, but were rather independent of loading sequence. Cold expansion (2.5–3.0%) significantly improved life in all cases considered—a factor of about 5 at the lower stresses. Interference fit, by itself, also gave large increases in life, progressively increasing with amount of interference—the improvement factor being about 10 at 0.8% interference. A combination of the two was even more effective in prolonging life, giving life improvements of 40–50 times at some stress levels.

Some of these results agree with those of the present work on 100% - load - transfer joints, others do not. The present results indicate *no* improvement in life with cold expansion; the difference between this and Schwarmann's result may possibly have to do

with the levels of fastener bearing load. The present specimen used a single fastener whereas Schwarmann's specimens had four fasteners, and hence a lower bearing load, which, in light of his result that life improvements decreased with increasing stress level, may, at least in part, resolve the apparent conflict. There is good agreement, however, on the influence of interference fit where mean lives increased progressively with degree of interference and more so in the presence of cold expansion.

A test program reported by Phillips [4, 11] considered a large number of variables, mainly concerning the cold expansion process. All his fatigue tests were made under constant-amplitude loading, and of some relevance are the results on 2024 aluminium alloy. For zero-load-transfer single-layer specimens in which the holes had been cold expanded, the use of 0.5% interference fasteners *decreased* (by a factor of about 4) the life compared with the use of neat-fit fasteners. This was certainly not the case with the present low-load-transfer specimens. It is interesting to note that Phillips reported the failure locations as at the specimen edges, away from the holes, which, in itself, would indicate that whatever processes were used to influence the region of the holes there should be *no* significant difference in the life. For high-load-transfer three-layer specimens Phillips found that, with neat-fit fasteners, cold expansion *decreased* the life (a factor of nearly 2) which coincides fairly well with the present results that cold expansion, by itself, does not improve life in high-load-transfer joints. With the insertion of 0.5% interference fasteners in the cold-expanded holes the experiments of Phillips gave an improvement in life, as did the present work.

A similar test program to that of Phillips has been conducted by Moore [5] on 2219 aluminium alloy, again, using only constant-amplitude loading, in which a large number of joint variables were examined including several percentages of load transfer. A single layer of metal was used for zero-load-transfer specimens, 100%-load-transfer specimens were comprised of three layers, and intermediate percentage load transfer specimens had two layers. Multiple regression analyses were made which indicated that, overall, interference is more effective than cold expansion in enhancing fatigue life. With 2% cold expansion or interference, the cold-expanded life improvement was a factor of about 2, whereas the factor for the interference fasteners was approximately 5. Although not giving the same numerical improvements, the present results show a similar trend, namely, that interference-fit fasteners are more effective than cold expansion of fastener holes in increasing the fatigue life of joints.

Ozelton and Coyle [12] have reported constant-amplitude tests at one stress level on 7050 aluminium alloy single-layer single-hole zero-load-transfer specimens using both cold expansion of the hole and interference-fit fasteners. The base condition of no cold expansion with a neat-fit fastener was not examined but other combinations of cold expansion and interference were tested. The results showed that interference fit (0.6%) was more effective than cold expansion (probably about 4%) in increasing life, and that a combination of the two processes was even more effective. The first of these conclusions, that interference fit is more effective than cold expansion in life enhancement agrees with the present results at both levels of load transfer, but the second conclusion of the synergism of the two processes agrees only with the 100%-load-transfer case of the present work.

Similar test conditions were examined by Rich and Impellizzeri [13] but on 7075 aluminium alloy single-layer zero-load-transfer specimens using spectrum loading.

Specimens with holes cold expanded approximately 4.5% and with clearance fasteners gave the same life as those without cold expansion but with fasteners having an interference of about 1%.

In summary, the published work indicates:

(i) variability in the effectiveness of cold expansion to improve fatigue life,

(ii) interference-fit fasteners give a higher and more-certain improvement in life compared with the use of cold expansion,

(iii) the combination of cold expansion and interference fit may give larger improvements in life than either process alone,

(iv) improvements in life are dependent on the joint and cyclic loading details.

Many of the results of the present work are covered by these statements.

6. CONCLUSIONS

1. The effectiveness of hole cold expansion in enhancing fatigue life is markedly dependent on the degree of load transfer in the specimen joint. With low-load-transfer specimens a life improvement factor of about 4 was obtained, but with 100%-load-transfer specimens the process was totally ineffective.

2. The use of interference-fit fasteners extended the fatigue life of low-load-transfer specimens by a factor of about 6 and was independent of the degree of interference. However, with 100%-load-transfer specimens the life improvement depended on the degree of interference, being ineffective at 0.5% but progressing to a 5-fold increase in life at an interference of 3.0%.

3. The combination of hole cold expansion and fastener interference gave an improvement in life in low-load-transfer specimens by a factor of about 6. With 100%-load-transfer specimens the factor ranged from about 5 to 40 and increased with degree of interference.

4. The use of interference-fit fasteners did not prevent interfacial fretting, with its resultant fatigue fracture, in low-load-transfer specimens—hence the borderline increase in life by using interference fasteners in cold expanded holes. Measures to alleviate the fretting were ineffective and it appears that good load transfer (through friction) and life improvement, in multi-layer joints, are incompatible aims.

5. Interfacial fretting occurred in 100%-load-transfer specimens but not to the extent of dominating failure. Life improvements with these joints should therefore be greater than with low-load-transfer joints and this was comfirmed experimentally.

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Table 1. Cold-expansion and interference-fit details

(a) hole diameters

Initial diameter (all holes)	: 8.36/8.37 mm
Final diameter (after cold expansion [if applicable] and reaming, and before fastener insertion)	: 8.81/8.82 mm

(b) cold expansion

Mandrel designation	: CBM-10-2-N-1-20-VI
Split sleeve designation	: 10-2-N-23F
Degree of expansion	: 4.0%

(c) fastener diameters

Neat-fit	: 8.79/8.80 mm
0.5% interference	: 8.86/8.87 mm
1.5% interference	: 8.94/8.95 mm
3.0% interference	: 9.08/9.09 mm

Table 2. Spectrum fatigue lives of low-load-transfer joint specimens

(a) bare metal contact at faying surfaces

Cold expansion (%)	Fastener interference (%)	Fatigue life (flight hours)	Log. average fatigue life (flight hours)
zero	zero	2375 2441 2697 3089	2636
	0.5	15667 16530 17004 17285	16610
	1.5	14375 15393 15648 17703	15735
4.0	zero	10041 10103 11532 12084	10904
	0.5	10389 16779 19662 20471	16275
	1.5	9765 15727 16384 21635	15275

(b) anti-fretting measures at faying surfaces
cold expansion : 4.0%
fastener interference : 1.5%

Anti-fretting measure	Fatigue life (flight hours)	Log. average fatigue life (flight hours)
Cold expand, re-polish faying surfaces, insert fasteners.	13163 14740	13929
Counterbore side plate holes and radius side plate edges, cold expand, insert fasteners.	15497 15973	15733
Interleave "Screenbak", cold expand, insert fasteners.	18214 25919	21728
Cold expand, re-polish faying surfaces, interleave "Screenbak", insert fasteners.	16414 19006	17662

Table 3. Ratios of mean lives of low-load-transfer joint specimens

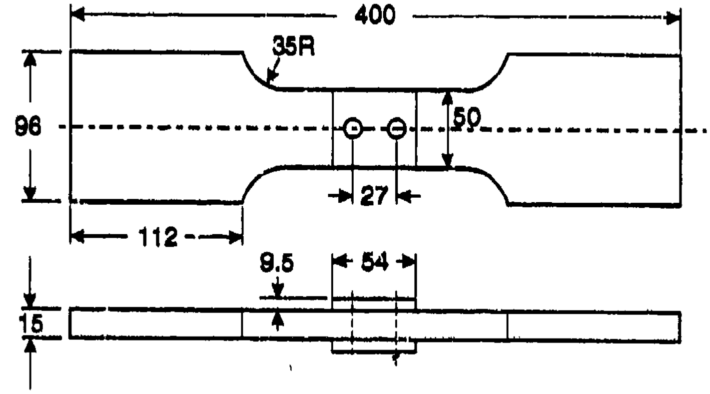
Comparison			Ratio of mean lives
4% cold expansion / zero cold expansion	for	: zero fastener interference	4.14
		: 0.5% " "	0.98
		: 1.5% " "	0.97
0.5% fastener interference / zero fastener interference	for	: zero cold expansion	6.30
		: 4% " "	1.49
1.5% fastener interference / zero fastener interference	for	: zero cold expansion	5.97
		: 4% " "	1.40
1.5% fastener interference / 0.5% fastener interference	for	: zero cold expansion	0.95
		: 4% " "	0.94
4% cold expansion and 0.5% fastener interference / zero cold expansion and zero fastener interference			6.17
4% cold expansion and 1.5% fastener interference / zero cold expansion and zero fastener interference			5.79

Table 4. Spectrum fatigue lives of 100%-load-transfer joint specimens

Cold expansion (%)	Fastener interference (%)	Fatigue life (flight hours)	Log. average fatigue life (flight hours)
zero	zero	848 884 914 1373	985
	0.5	613 695 877 948	771
	1.5	2181 2198 3238 4167	2836
	3.0	4940	4940
4.0	zero	950 990 1242 1848	1212
	0.5	3426 4235 5008 6528	4667
	1.5	6728 9843 13360 14970	10728
	3.0	33603 48637	40427

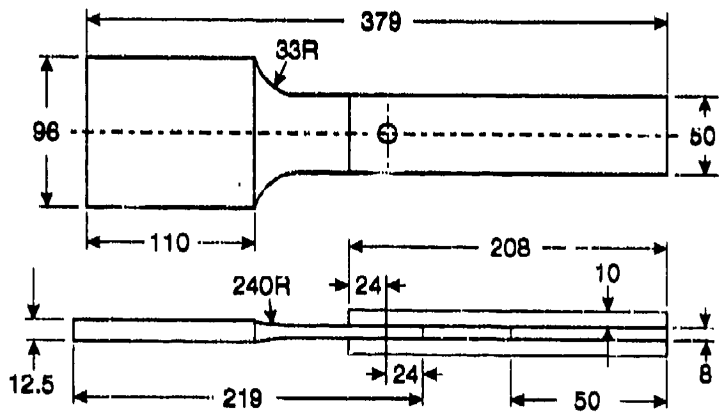
Table 5. Ratios of mean lives of 100%-load-transfer joint specimens

Comparison			Ratio of mean lives
4% cold expansion / zero cold expansion	for	: zero fastener interference	1.23
		: 0.5% " "	6.05
		: 1.5% " "	3.78
		: 3.0% " "	8.18
0.5% fastener interference / zero fastener interference	for	: zero cold expansion	0.78
		: 4% " "	3.85
1.5% fastener interference / zero fastener interference	for	: zero cold expansion	2.88
		: 4% " "	8.85
3.0% fastener interference / zero fastener interference	for	: zero cold expansion	5.02
		: 4% " "	33.36
4% cold expansion and 0.5% fastener interference / zero cold expansion and zero fastener interference			4.74
4% cold expansion and 1.5% fastener interference / zero cold expansion and zero fastener interference			10.89
4% cold expansion and 3% fastener interference / zero cold expansion and zero fastener interference			41.04

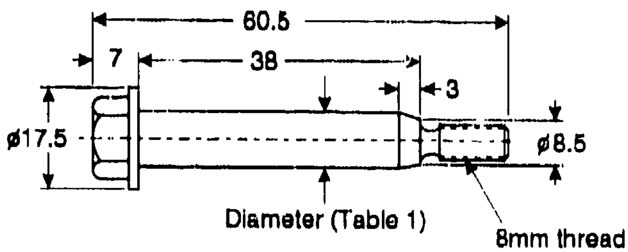


(a) low-load-transfer joint specimen

Dimensions in mm



(b) 100% - load-transfer joint specimen



(c) Fastener

FIG. 1. Multi-layer fatigue specimens

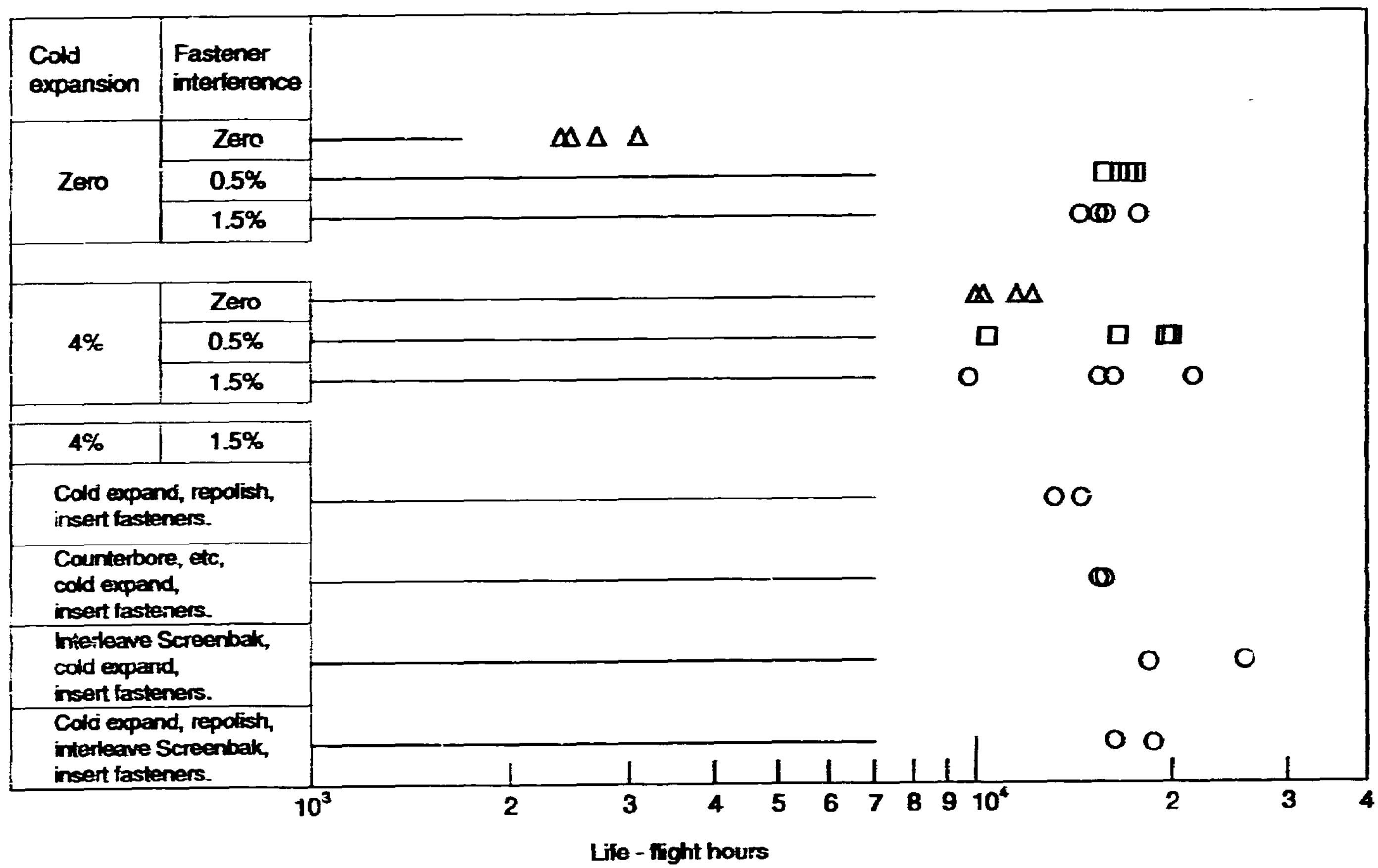
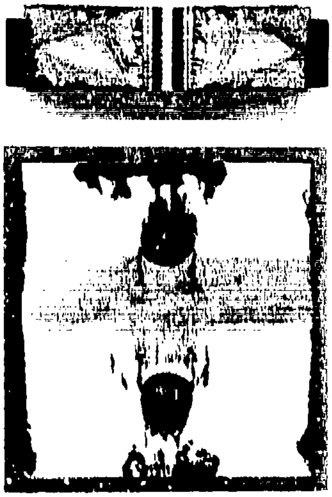
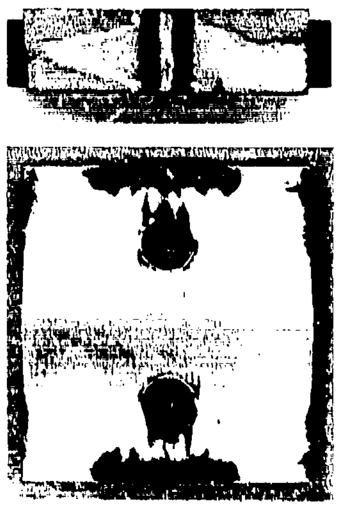


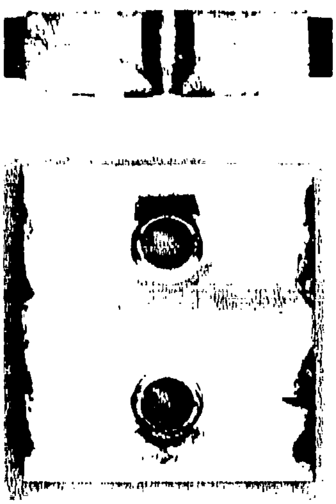
FIG. 2 Fatigue test lives: low-load-transfer joint specimens



(a) neat-fit fasteners.

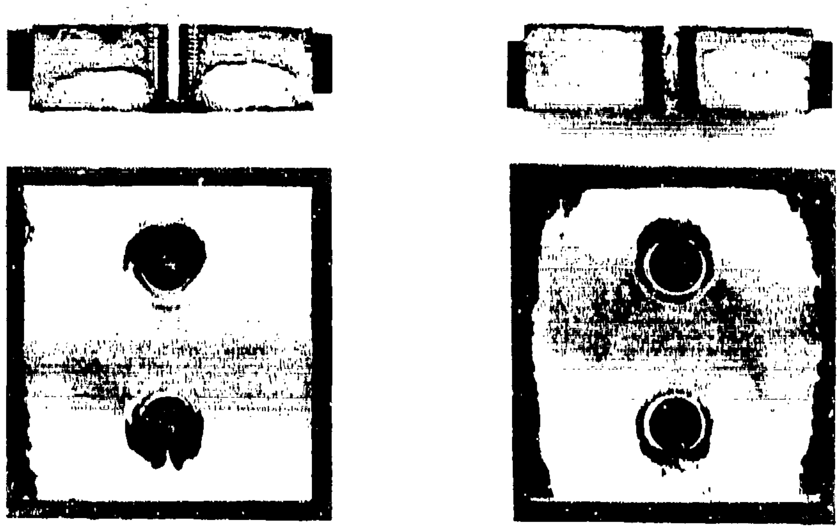


(b) 0.5% interference fasteners.



(c) 1.5% interference fasteners.

FIG. 3. Fractures and side plate wear in low-load-transfer specimens, no cold expansion of holes. x1



(a) neat-fit fasteners.

(b) 0.5% and 1.5% interference fasteners.

FIG. 4. Fractures and side plate wear in low-load-transfer specimens, 4% cold expansion of holes.
x1

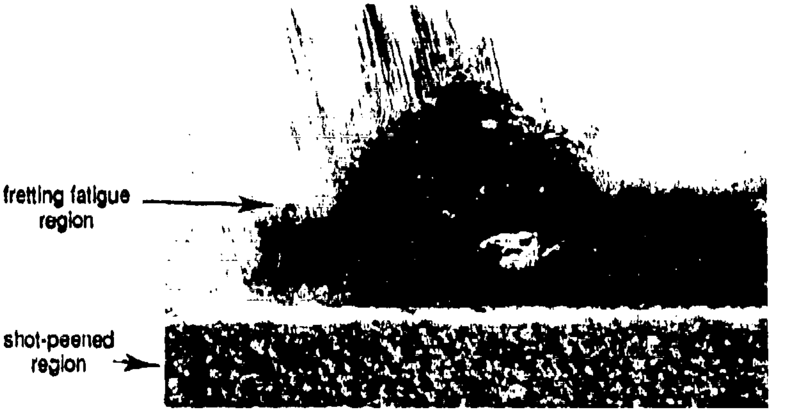


FIG. 5. Severe fretting and fatigue fracture at end of side plate, low-load-transfer specimen.
4% cold expansion, 0.5% fastener interference.
x8

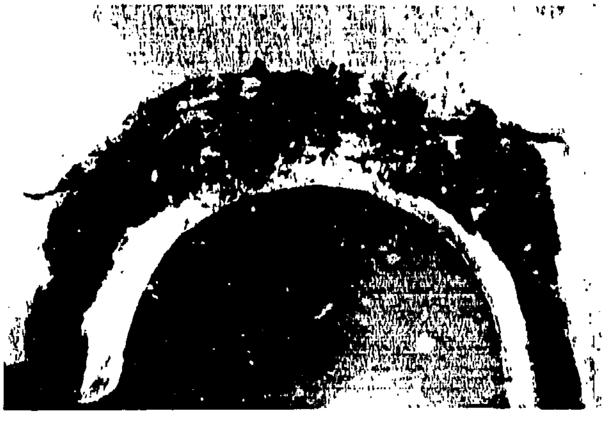
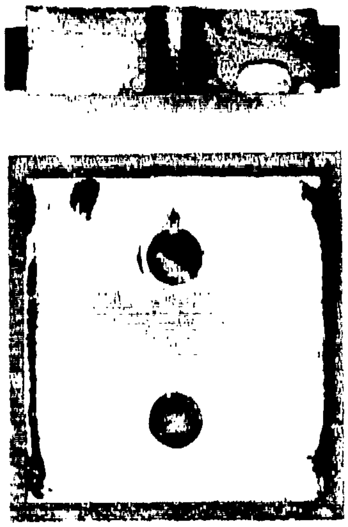
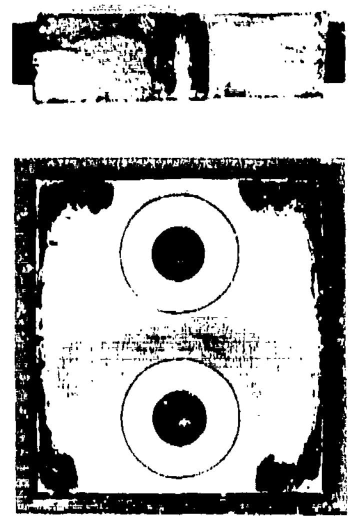


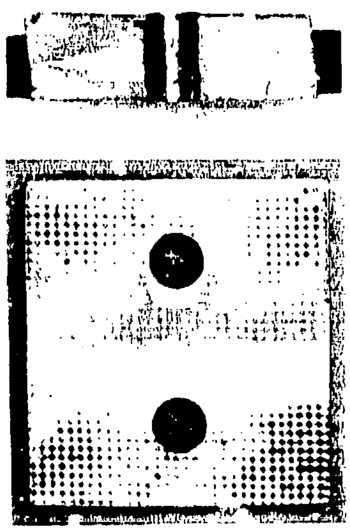
FIG. 6. Fretting fatigue cracks adjacent to fastener hole, low-load-transfer specimen.
4% cold expansion, 1.5% fastener interference.
x8



(a) cold expanded, out-of-plane displacements removed by polishing, re-assembled.



(b) side plate edges radiused and holes counterbored before cold expansion and assembly.



(c) (i) 'Screenbak' inserted between side plates and specimen before cold expansion
(ii) cold expanded, out-of-plane displacements removed by polishing, 'Screenbak' inserted, re-assembled.

FIG. 7. Fractures and side plate wear of low-load-transfer specimens with 1.5% interference fasteners. Measures to reduce fretting around fastener holes.
x1

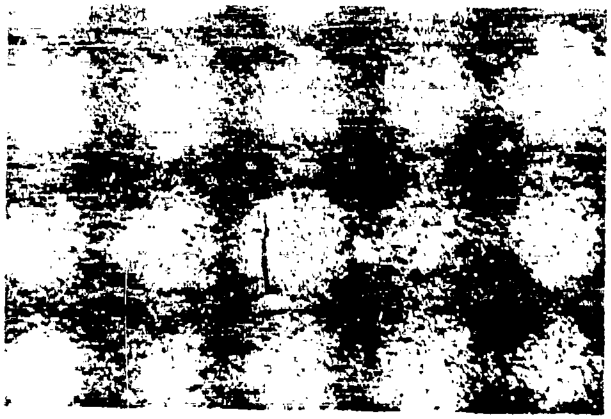


FIG. 8. Fatigue fracture initiated within 'Screenbak' abraded region of low-load-transfer specimen with 4% cold expansion and 1.5% fastener interference.
x8

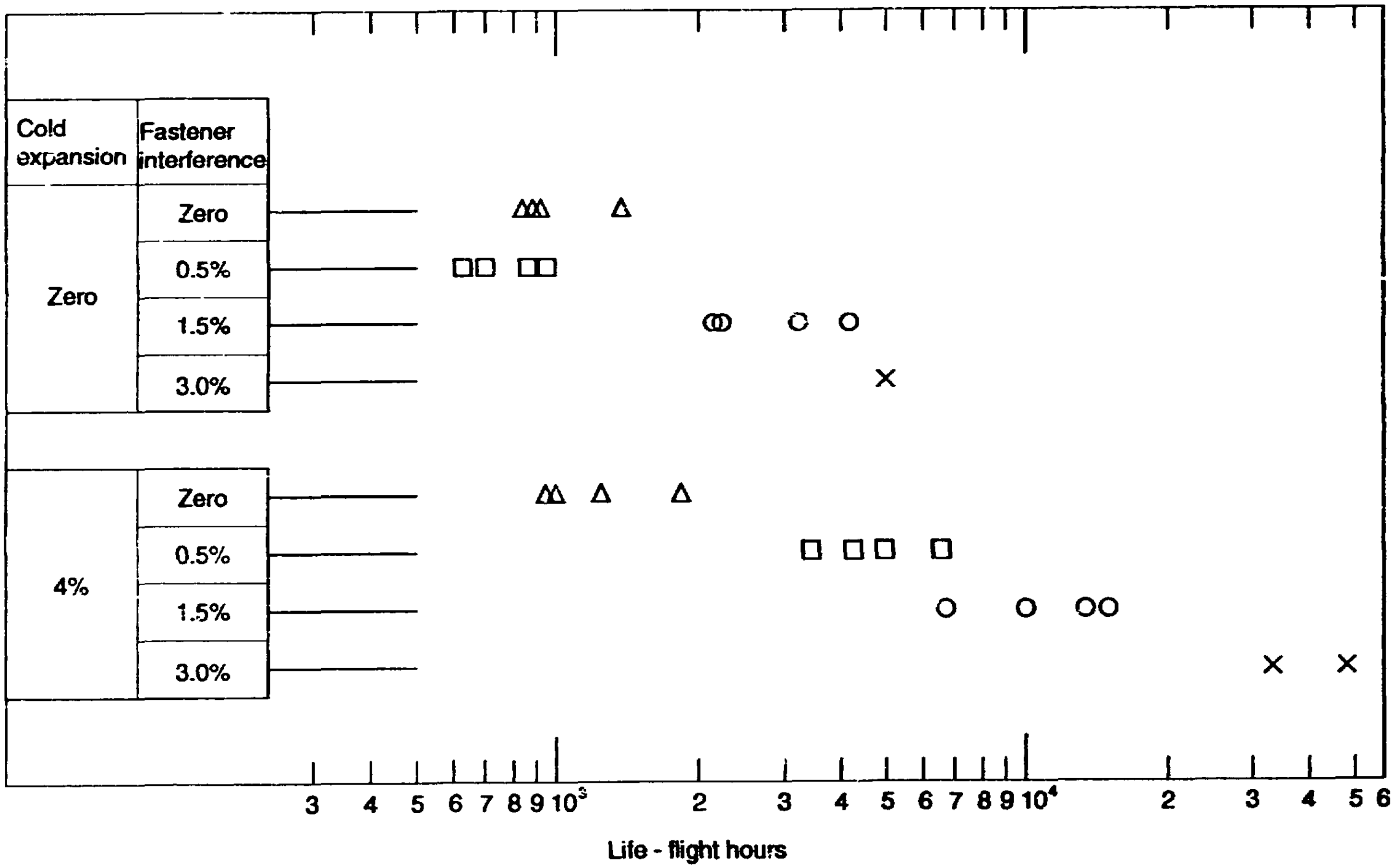


FIG. 9. Fatigue test lives: 100%-load-transfer joint specimens

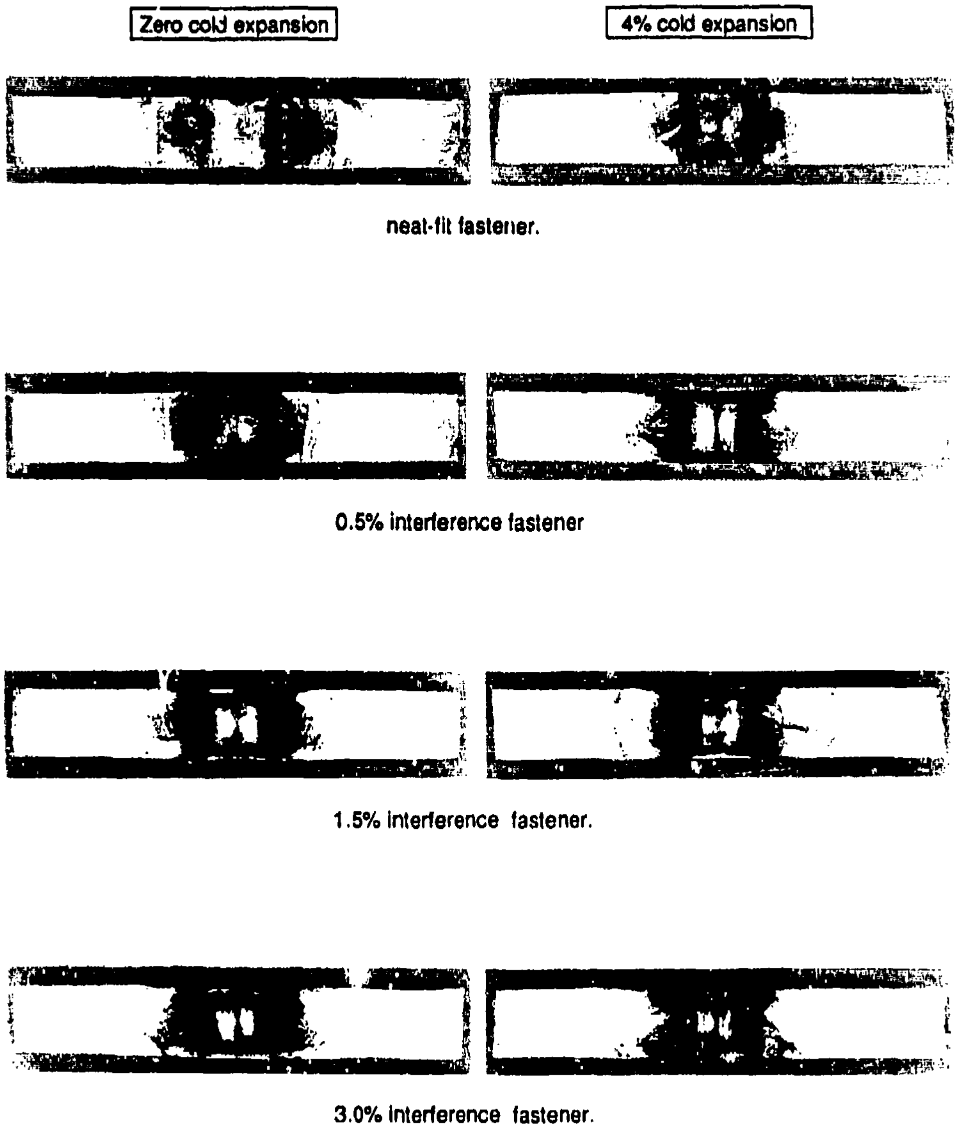


FIG. 10. Fractures of 100%-load-transfer specimens.
x1.5

(a) no cold expansion, neat-fit fastener.

(b) 4% cold expansion, neat-fit fastener.

(c) no cold expansion, 1.5% interference fastener.

(d) 4% cold expansion, 3% interference fastener.

FIG. 11. Face fretting and fracture path in 100%-load-transfer specimens. x1

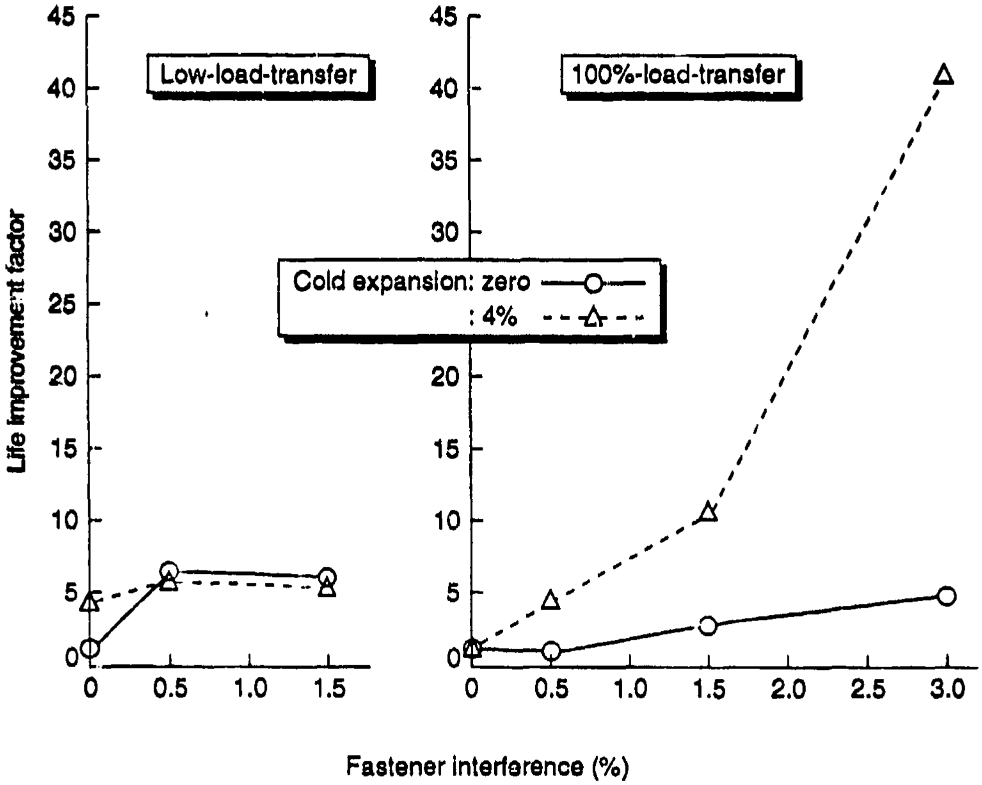


FIG. 12. Fatigue life improvement by hole cold expansion and fastener interference (compared with no cold expansion and neat-fit fasteners).

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Fatigue life	Interference fit devices	
Holes (openings)	Fasteners	

16. ABSTRACT

The influences of both hole cold expansion and interference-fit fasteners for extending the fatigue life of multi-layer aluminium alloy joint specimens under variable-amplitude loading have been examined experimentally. Improvements in fatigue life were markedly dependent on the degree of load transfer in the specimen joint. The cold expansion of fastener holes enhanced fatigue life in low-load-transfer joints but not in 100%-load-transfer joints. The use of interference-fit fasteners, especially at high degrees of interference, was an effective means of life improvement irrespective of proportion of load transfer. Interfacial fretting limited the improvement in fatigue life of low-load-transfer joints to a factor of about 6, and, although some fretting occurred in 100%-load-transfer joints it was not determinative, and a 40-fold increase in fatigue life was obtained with a combination of hole cold expansion and interference-fit fastener.

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